Research Note

Importance of Pulsar Observations for Planetary Physics

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The possibility of observing planetary systems of pulsars is examined. The expected perturbation in the time of arrival of pulses is computed and the detectability is discussed.

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One of the main limitations of planetary physics is that practically all experimental observations have been confined to the solar system. Any direct or indirect experimental evidence regarding other planetary systems would be of the utmost importance.

The possible existence of pulsar planetary systems has been suggested for CP 1133 by Davies et al (1969) and for NP 0532 by Richards et al (1970), who have been criticized by Papaliolios et al (1970). However, we think that the importance of systematic pulsar observations has not been thoroughly stressed.

Pulsars are generally believed to be rotating neutron stars resulting from a supernova explosion. The problem of the survival of a planetary system through all stages of stellar evolution up to the final explosion has been considered by some authors [see in particular Colgate (1970) and Rees et al (1971)]. These works indicate that a planet can survive provided that (a) the mass ejected in the explosion is less than half of the total mass of the star, as a consequence of the virial theorem, and (b) that the periastron r of the planet satisfies the relation

$$r \gtrsim 2.5 \times 10^{12} \left(\frac{m}{M_{\oplus}}\right)^{-2/9} \text{ cm}$$

where m is the mass of the planet, which provides that the planet is not destroyed by the explosion. Condition (a) seems to be satisfied by the Crab Nebula which is the only supernova remnant for which systematic observations of the mass have been performed. Condition (b) is fulfilled by all planets of the solar system except Mercury and the asteroids. It seems, then, that it is possible that some pulsars have a planetary system.

The center of mass of a system composed of a star surrounded by planets does not, in general, coincide with the center of mass of the star. It follows that the star rotates around the center of mass of the system. This motion can be observed by measuring in an inertial frame (for instance, the barycenter of the solar system) the times of arrival of the pulses from the star, because the perturbation caused by the planets induces a sinusoidal modulation.

Let $P = P(t)$ be the period of a pulsar. If the pulsar had no proper motion with respect to the observer, the number N of pulses measured in time T would be given by

$$N(T) = \int_{o}^{T} \frac{dt}{P(t)} \tag{1}$$

If there is a periodic motion of the pulsar around the barycenter, the number of pulses N_m effectively measured would be different from N and the function $\Delta N = (N-N_m)$ would preserve the same periodic structure of the function which describes the motion around the barycenter. In the simple case of only one planet (two-body system), the Fourier analysis of $\Delta N(t)$ will show a peak corresponding to the period of revolution of the planet. The presence of a peak is independent of a secular change of the period, which is observed in many pulsars and is interpreted to be due to the slowing down of the neutron star. In the case of more complex systems, more peaks are to be expected and their location and intensity can, at least in principle, give information on: (a) the number of planets, (b) their periods of revolution, and (c) the quantity $\ell = \frac{m\bar{r}}{M}$, the displacement of the barycenter. (M is the mass of the pulsar and $\bar{r}$ the mean distance between the pulsar and the planet.)

An approximate value of $\Delta N(t)$ for the case of one planet is given by

$$\Delta N_{Pl} \simeq \frac{4\ell t}{cP_{Pl}P} \qquad (2)$$

where P_{Pl} is the period of revolution of the planet, and t the time of observation. Table 1 lists the values of ΔN for different pulsars having periods ranging from 0.23 to 1.96 seconds. The perturbations are assumed to be caused by planets with the same mass and orbit as Mars ($\bar{r} \sim 2.3 \times 10^{13}$ cm, $m \sim 6.4 \times 10^{26}$g) and as Jupiter ($\bar{r} \sim 7.7 \times 10^{13}$ cm, $m \sim 1.9 \times 10^{39}$ g). The mass of the pulsar is assumed to be equal to 1 $M_\odot$, and $t \simeq 1$ year $\simeq$ 3×10^7 seconds.

Expanding P(t) in Taylor series and considering only the first two terms, $P(t) = P_o + \dot{P}t$, from Eq. (1) we have

$$N(t) = \frac{1}{\dot{P}} \ln \frac{P_o + \dot{P}t}{P_o} \sim \frac{t}{P_o} - \frac{1}{2}\frac{\dot{P}}{P_o^{\,2}}\, t^2 \qquad (3)$$

It follows that the error in N arising from uncertainties in P_o and $\dot{P}$ is given by

$$\Delta N_{err} = \left[\left(-\frac{t}{P_o^2} + \frac{\dot{P}}{P_o^3}t^2\right)^2 \Delta P_o^2 + \frac{1}{4}\frac{t^4}{P_o^4}\Delta\dot{P}^2\right]^{1/2} \qquad (4)$$

ΔN_{err} as calculated from (4) is listed in the last row of Table 1. The values of P_o, ΔP_o, $\dot{P}$, $\Delta\dot{P}$ are taken from Ruffini and Wheeler (1971). The choice of t = 1 year was made because this is a time of the same order as the one for which $\dot{P}$ is measured, and also because it is a natural unit for the period of the revolution of planets.

Comparing the values of ΔN_{Pl} and ΔN_{err}, we find that a planet like Jupiter would induce a perturbation larger than the uncertainty attributable to the observational errors in P_o and $\dot{P}$. On the contrary, for a planet like Mars

$$\Delta N_{Pl} < \Delta N_{err}$$

and the inequality could be reversed only if the measurements of the pulsars' periods and their derivatives could be improved.

The most accurate observations of pulsar phases have been obtained for NP 0532 and PSR 0833, respectively, in the Crab Nebula and in the Vela X supernova remnant. These objects are the fastest pulsars ($P_{NP\ 0532} \simeq 33$ msec, $P_{PSR\ 0833} \simeq 89$ msec) and most likely also the youngest. They have been observed to exhibit sudden discontinuities of the period (glitches), which are generally interpreted to be of internal origin. A complete theory of these glitches is still missing, but there is general agreement* that this kind of event is to be expected more frequently in young objects and, in fact, has not been observed in other pulsars but NP 0532 and PSR 0833.

The presence of glitches, or a large variation of $\dot{P}$ with time, as in the case of NP 0532 for which $\ddot{P}$ is measurable, makes more difficult the observation of planetary systems. Because both effects are more evident in young pulsars, it follows that the most promising way for finding a planetary system is to look at old pulsars.

Thus far, more than 50 pulsars have been detected. They offer an interesting statistical sample for observing or excluding the presence of planetary systems. It seems that it would be extremely interesting to make a systematic phase analysis for the largest number of pulsars. The analysis should cover a period of several years so that long-period perturbations of planets could be detected. Although such a program is difficult and relatively expensive, it is our opinion that the results could be extremely rewarding.

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* See for instance Pines (1970).

Table 1. Phase shifts caused by perturbations of a planet with the mass and orbit of Jupiter or Mars. ΔN_{err} is the phase uncertainty because of the errors in the period P_o and in its derivative $\dot{P}$.

	PSR 1929+10	AP 0823+26	CP 0328	PSR 2045-16
P_o	0.2265170159 sec. $\pm$ 0.2 nsec	0.53065958655 sec. $\pm$ 0.05 nsec	0.71451855076 sec. $\pm$ 0.02 nsec	1.9615663519 sec. $\pm$ 0.4 nsec
$\dot{P}$	$(2.307\pm0.003)\times10^{-19}$ sec/sec	$(6.0134\pm0.001)\times10^{-18}$ sec/sec	$(1.496\pm0.006)\times10^{-19}$ sec/sec	$(1.10\pm0.03)\times10^{-17}$ sec/sec
ΔN_{Pl} (Jupiter)	3.68 pulses/year	1.56 pulses/year	1.16 pulses/year	0.44 pulses/year
ΔN_{Pl} (Mars)	2.28×10^{-3} pulses/year	9.6×10^{-4} pulses/year	7.2×10^{-4} pulses/year	2.64×10^{-4} pulses/year
ΔN_{err}	1.2×10^{-1} pulses/year	5.6×10^{-3} pulses/year	1.2×10^{-3} pulses/year	3.28×10^{-3} pulses/year

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